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Deformational style and hydrocarbons trapping mechanism of the sub Himalayan frontal ranges near Fateh Jhang, Punjab, Pakistan

Salman Ahmed Khattak[1,2*], Gohar Rehman[2], Sajjad Ahmad[2], Muhammad Faisal Jan[2], Salman Khurshid[2] and Ahmad Ghani [2]

[1] Department of Geology, University of Haripur

[2] Department of Geology, University of Peshawar

**Corresponding author's email: salman@uoh.edu.pk*

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Abstract

This research targets the Fateh Jang area, part of Sub-Himalayan Frontal Ranges in the foothills of Main Boundary Thrust (MBT) Fault in the Upper Indus Basin, Pakistan. The purpose of this research is to interpret the deformational style using the 2D seismic data to delineate the hydrocarbons trapping mechanism developed in response to the crustal adjustments due to the crustal deformation by the Himalayan Orogeny. Subsurface structural geology of Bhal Sayedan oil field is interpreted by using eight 2D seismic line data and formation tops data from well Bhal Sayedan-02. The 2 D seismic lines were interpreted to reveal the 3 D subsurface structure of the Bhal Sayedan area in the software MOVE (2D & 3D). Seismic interpretation in 2 D reveals that the Bhal Sayedan area consists of fold and thrust geometry and general trend of the thrust faults is northeast-southwest due to southeast northwest compressive stresses. The Bhal Sayedan area shows an average crustal shortening of ~3900m along the two south verging blind thrust faults namely Ajjuwala thrust fault (throw 550m) and Jafar thrust fault (throw 400m) by bringing the Eocene rocks over the Miocene rocks. The 3D model reveals that the Bhal Sayedan anticline is a fault propagation fold lying between the Ajjuwala and Jafar thrust faults and hence has four way closure making it an ideal target for the hydrocarbons trapping.

Keywords: Seismic interpretation, Sub-Himalayas, 3D modeling, Deformational style, Bhal Sayedan anticline, Hydrocarbons trapping mechanism.

1. Introduction

This study attempts to decipher the subsurface structural geology of the Bhal Sayedan area by using 2D seismic data and well data. Tectonically the Bhal Sayedan oil field lies in the foothills of Kalachitta Ranges which is part of the Northern Potwar Deformed Zone (NPDZ). NPDZ lies in the Punjab province, located in the northern part of Potwar Plateau, which is the integral part of Sub-Himalayan foreland fold and thrust belt in Pakistan; characterized by spectacular features of compressional and transpressional deformation developed due to the collision of Indo-Pak plate with Eurasian plate (Ahmed et al., 2009) (Fig. 1). The fractured carbonate of Eocene age i.e. Kohat, Kuldana, and Chorgali formations are the major producing reservoirs in the Bhal Sayedan area.

The stratigraphy of the Potwar Plateau is well defined from outcrops but we do not have enough stratigraphic details in Northern Potwar Deformed Zone as we lack deep drilling in NPDZ but stratigraphy is well defined with the help of seismic surveys and sections (Eames, 1952). Stratigraphic succession in the study area is divided into two major sequences, Middle to Late Eocene and Early to Late Miocene. During the Eocene age shallow marine to lagoonal sediments were deposited on the earlier deposited sediments. A thick sequence of carbonates and clays were deposited in the Western and Central Potwar

Plateau thinning towards the west (Lewis, 1937). The period of uplift and erosion corresponds to major collision between Indian and Eurasian plates in the Eocene age and continues in the Himalaya far deep in the older rocks with angular relation (Seeber et al., 1981). The collision resulted in the deposition of fluvial time transgressive deposits of Rawalpindi and Siwaliks groups during the uplift of Himalaya (Johnson et al., 1979). In the study area, the thickness of formations is not uniform it may be due to thrusting nature of the NPDZ. These sedimentary rocks are well developed and well exposed along the road cutting at the Bhal Sayedan near Fateh Jhang (Punjab). The study area mainly consists of sandstone, limestone, shale, marl and some conglomeratic beds. The Eocene age includes Kohat, Kuldana and Chorgali formations (Shah, 2009) (Table 1).

The objectives of this research work is the seismic data interpretation in order to understand the subsurface structural geometry of the area which will help in describing the deformational style of the region and delineating the subsurface target horizons for hydrocarbons accumulations. Integration of seismic and well data to enhance the precision of the interpretation process in order to identify the depth of key horizons and to construct the 3D model of the key horizons including the reservoir rocks.

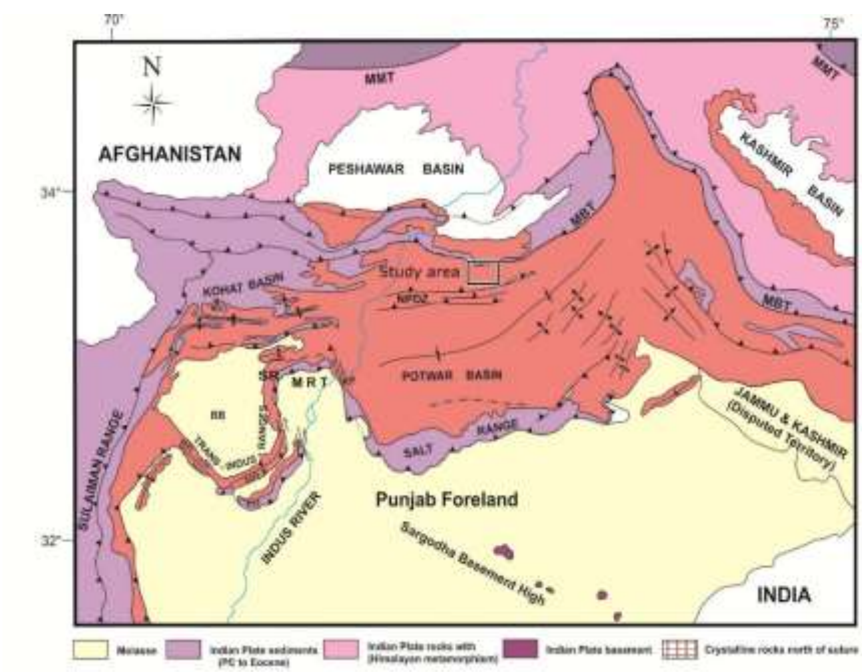

Fig.1. Generalized tectonic map of NW Himalayan Foreland Fold and Thrust Belt (modified after Kazmi & Rana, 1982). Inset shows the location of the study area.

2. Data and method

The following geological and geophysical data have been used for the stratigraphic and structural interpretation of the subsurface horizons.

1) Base map (Fig. 2).
2) Migrated seismic sections (SEG-Y) were used i.e. the strike line (905-BSL-109), oblique lines (905-BSL-110, 971-BSL-13, 981-BSL-14) and dip lines (981-BSL-17, 981-BSL-19,981-BSL-20, 991-BSL-28) (Table 2).
3) Formation tops data of Bhal Sayedan well-02.

Each trace of SEG-Y was first converted into start and end points, which was then converted into shape files and uploaded into the MOVE software to rectify in WGS 84. After uploading, these seismic sections were converted into depth sections. The selective reflectors were marked as formations at the given depths using formations tops from the Bhal Sayedan well-02.

The tops were identified by tying the prominent reflectors in the seismic data with the surface exposures of the rocks in the north. One of the confidential seismic line which extended to the north where the stratigraphy was well exposed was used only for the purpose of identification of the reflectors. On the basis of the continuity of selective reflectors in the seismic sections and repetition of the formations in the well, faults were marked. Using the marked seismic sections, the polygons were made for each horizon (formation) in all eight seismic sections (Fig. 3). Following this the 2D structural sections were drawn. Afterwards, all eight seismic sections were tied up in the software to view the 3D perspective of the selective seismic reflectors. Subsequently, the 3D surfaces were constructed to delineate 3D model of the subsurface structures (Fig. 4). To determine the deformational style and hydrocarbons trapping mechanism the 3D model was transferred to "3D MOVE" for orientation analysis.

3. Results and discussions

Seismic interpretation is the transformation of seismic reflection data into a structural picture by the applications of corrections, migration and time depth conversion (Dobrin and Savit, 1988; Kearey et al., 2002; Zahid et al., 2014). Seismic reflection interpretation relies on identifying the reflectors and calculating their positions on the basis of geology of the survey area and correlations with the well data (Reynolds, 1977). Evaluation of the trapping styles is fundamental in the analysis of a prospect and an essential part in any successful oil and gas exploration program or resource assessment program (Oyeyemi and Aizebeokhai, 2015). Faults are significant tools in the trapping of hydrocarbons. The trapping configurations of the faults were presumed to be responsible for the creation of multiple reservoir compartments of hydrocarbons bearing formations (Ologe et al., 2014).

The 2D seismic interpretation led to the demarcation of three horizons i.e. Kuldana, Kohat and Murree formations of the Eocene and Miocene age respectively. The continuity of the horizons led to the identification of two major faults namely Jafar and Ajjuwala thrust faults running through all the seismic sections. The orientation of the faults and horizon displacements across the faults is northeast-southwest which show southeast northwest compressive stresses to be responsible for these two faults. These two blind thrust faults are probably linked to a single event of deformation in response to the Himalayan Orogeny.

Table 1. Composite stratigraphic chart of the study area.

Age	Formation	Symbol	Lithology	Subsurface thickness at Bhal Saydan Well-02
Pliocene	Chinji		Red Clays with subordinate ash grey or brownish grey Sandstone	
Miocene	Kamlial		Dark grey to greenish grey Sandstone with dark to maroon color Siltstone	
	Murree		Dark red to maron color Siltstone interbedded with Clay and grey color Sandstone	3411 m Top Eroded
Eocene	Kohat		Light grey argillaceous Limestone with Shale interbeds	82 m
	Kuldana		Variegated dominantly red Shale and grey Carbonate interbeds, Gypsum and Anhydrite horizons	255 m
	Chorgali		Dolomite Shale, Sandstone and thinly bedded Limestone and Marl alterations	80 m

Fig. 2. Base map of the study area showing the location of seismic lines and Bhal Sayedan well-02.

The anticlines which are the fault propagation folds lie on the apex of these two faults and form the potential zone of trap formation in the central anticlinal part named as Bhal Sayedan anticline sandwiched between the two faults.

These faults shows the displacements in the seismic sections, on the basis of which crustal shortening of ~3900m is calculated (Table. 3). The displacement along these faults created the closures for the Kohat Formation that acted as a reservoir.

The 3D surfaces of the Kohat Formation were constructed along with the associated faults on the basis of seismic data. The 3D surfaces show that the Bhal Sayedan area is structurally a south-verging thrust system comprises three blocks separated by the two thrust faults which are named as follows:

a. Ajjuwala anticline surface (towards the north)
b. Bhal Sayedan anticline surface (between the two thrust faults)
c. Jafar anticline surface (towards the south)
d. Ajjuwala fault (towards the north)
e. Jafar fault (towards the south)

The central 3D surface is named as "Bhal Sayedan anticline surface", which is between the thrust faults (Ajjuwala fault & Jafar fault) and is the main target horizon for the hydrocarbons exploration (Fig. 5). It is forming a perfect anticline, which is fault bounded with four way closure. Its back limb is gentle dipping as compared to fore limb which is short and propagated over the Jafar fault towards the south. The maximum elevation of this 3D surface is -3245m and minimum elevation is -3936m.

The area of this surface is 37.4 square km. The average strike of the surface is 277° while the average dip is 7° (Fig. 6). The Ajjuwala fault is a south verging fault which dissects the northern limb of the Bhal Sayedan anticline. The Ajjuwala fault is stacking Ajjuwala anticline over Bhal Sayedan anticline, making Bhal Sayedan anticline a firm trap. This fault plays a vital role in the structural geometry of the study area. This fault lies deep with its maximum elevation is -2840m and minimum is -4178m. The Ajjuwala fault is dipping 13° towards north, where the strike of the Ajjuwala fault is 281° (Fig. 7). The Ajjuwala anticline surface is a 3D surface which is an anticline and clearly closed from the four sides. Its back limb is long and gentle dipping while the fore limb is short and is propagated over the Ajjuwala fault towards the north (Fig 5). The Ajjuwala anticline surface has an area of 33.5 square km with maximum elevation of -2929m and minimum elevation of -3530m. The strike of this surface is 276° and the dip is 7° (Fig. 8). The Jafar fault is also a south verging fault that dissects the Jafar anticline towards north. Jafar fault also plays vital role in the structural geometry of the area. It brings the Bhal Sayedan anticline over Jafar anticline towards north, making Bhal Sayedan and Jafar anticlines more viable hydrocarbons leads (Fig. 5). This fault is deep in the surface at the depth of maximum elevation of -2788m and minimum elevation of -4500m. The average dip of the Jafar fault is 20°, where the strike of this fault is 277° (Fig. 9). The 3D surface of the Jafar anticline is towards the extreme south direction. It is broad gentle anticline, whereas Jafar fault dissected its northern limb. The average strike of the surface is 61° and the average dip of the surface is 7° (Fig. 10). This 3D surface has an area of 51.7 square km. This 3D surface has maximum -3808m elevation and minimum elevation is -4669m.

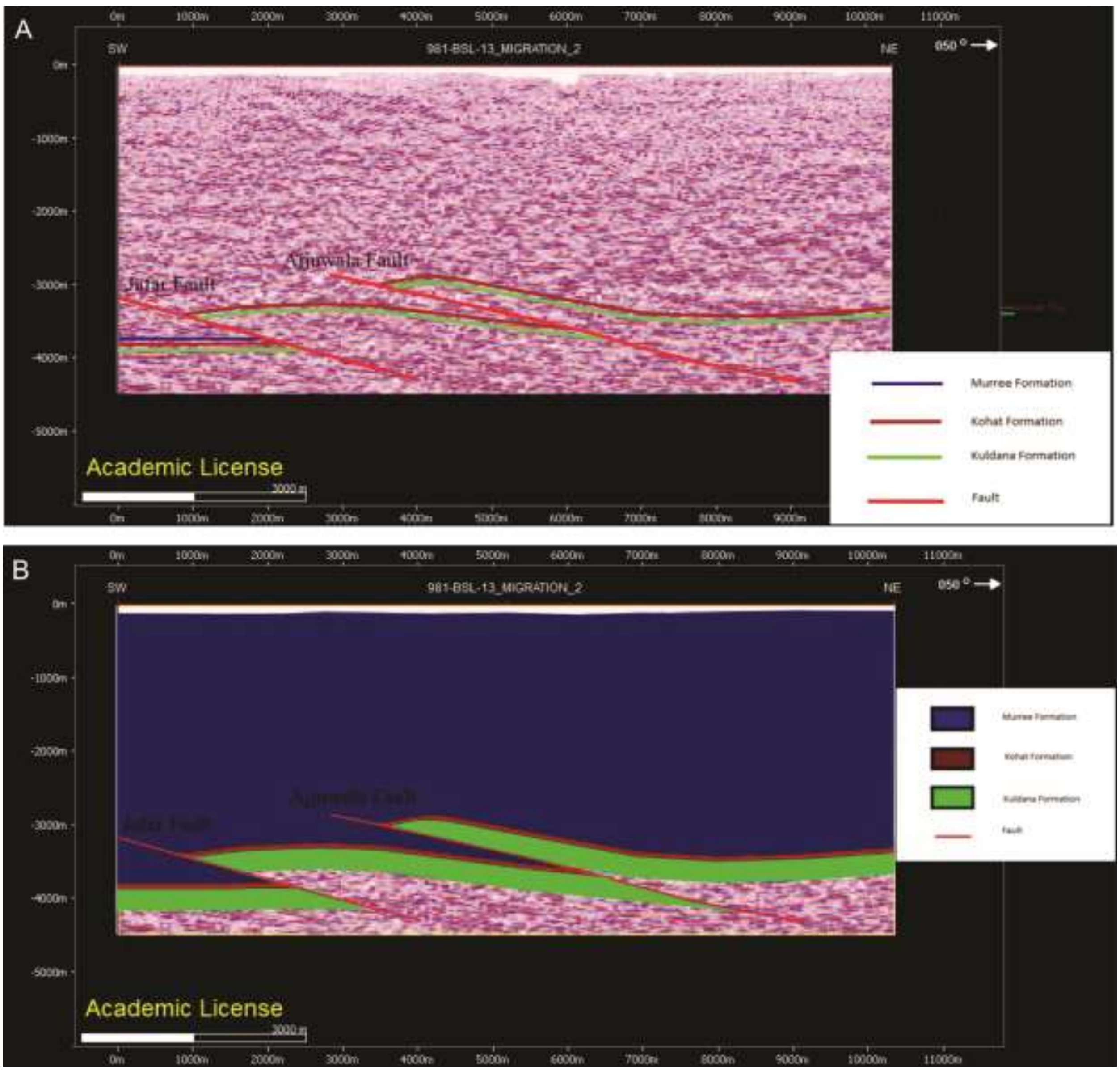

Fig. 3. A. Interpreted seismic section shows faults and horizons, B. Section shows polygons constructed of each horizon.

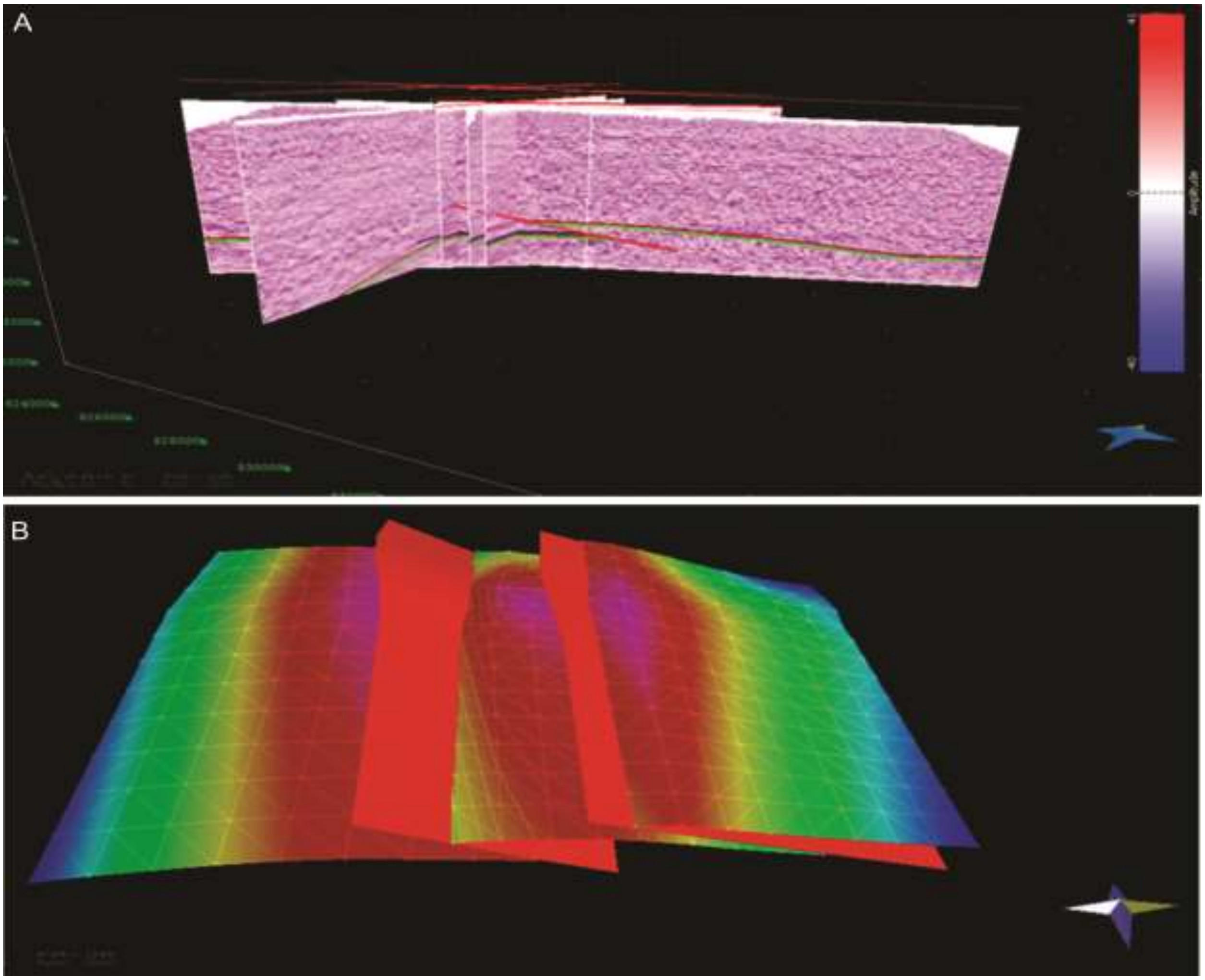

Fig. 4. A. 3D array view of the interpreted seismic lines, B. Shows subsurface 3D model of target horizon and the associated faults.

Table 2. Showing the length, depth and trend of the seismic lines.

Name of seismic line	Length of seismic line	Depth of seismic line	Trend of the seismic line
905-BSL-109	16920m	-4868m	Strike line trending east-west, at a deflection of 72° from north
905-BSL-110	14364m	-4867.8m	Oblique trending NE-SW, at a deflection of 57° from north
971-BSL-13	10372m	-4502m	Oblique line, the trend of which is NE-SW at 50° from north
981-BSL-14	8880m	-4383m	Oblique line, the trend of which is NE-SW at 50° from north
981-BSL-17	8891m	-4502m	Dip line trending north-south and is deflected from north at an angle of 6°
981-BSL-19	6519m	-4502m	Dip line and is trending north-south, at a little deflection of 5° from the north
981-BSL-20	7520m	-4502m	Trending north-south with a deflection angle of 6° from the north
991-BSL-28	9425m	-4502m	Dip line and its trend is north-south, with an angle of 5° from the north

Trapping mechanism in the Bhal Sayedan oil field were revealed to be fault assisted four way closure and possibly served as the trapping mechanism for the reservoirs. The Bhal Sayedan anticline surface is the principle structure responsible for hydrocarbons entrapment in the field. The 3D model reveals that the Bhal Sayedan anticline is a fault propagation fold lying between the Ajjuwala and Jafar thrust faults and hence has four way closure making it an ideal target for the hydrocarbons trapping.

Table 3. Showing the throw, heave and displacement of the seismic lines.

S.No	Name of seismic lines	Ajjuwala fault			Jafar fault		
		Throw	Heave	Displacement	Throw	Heave	Displacement
1	905-BSL-109 Strike line	305m	940m	990m	395m	2270m	2305m
2	905-BSL-110 Oblique line	220m	455m	505m	390m	2170m	2200m
3	971-BSL-13 Oblique line	625m	2700m	2770m	395m	1385m	1440m
4	981-BSL-14 Oblique line	555m	2175m	2245m	400m	1385m	1440m
5	981-BSL-17 Dip line	655m	2895m	2970m	415m	1225m	1295m
6	981-BSL-19 Dip line	655m	3110m	3180m	350m	1070m	1130m
7	981-BSL-20 Dip line	630m	2845m	2915m	380m	1040m	1110m
8	991-BSL-28 Dip line	775m	3650m	3730m	425m	1245m	1315m

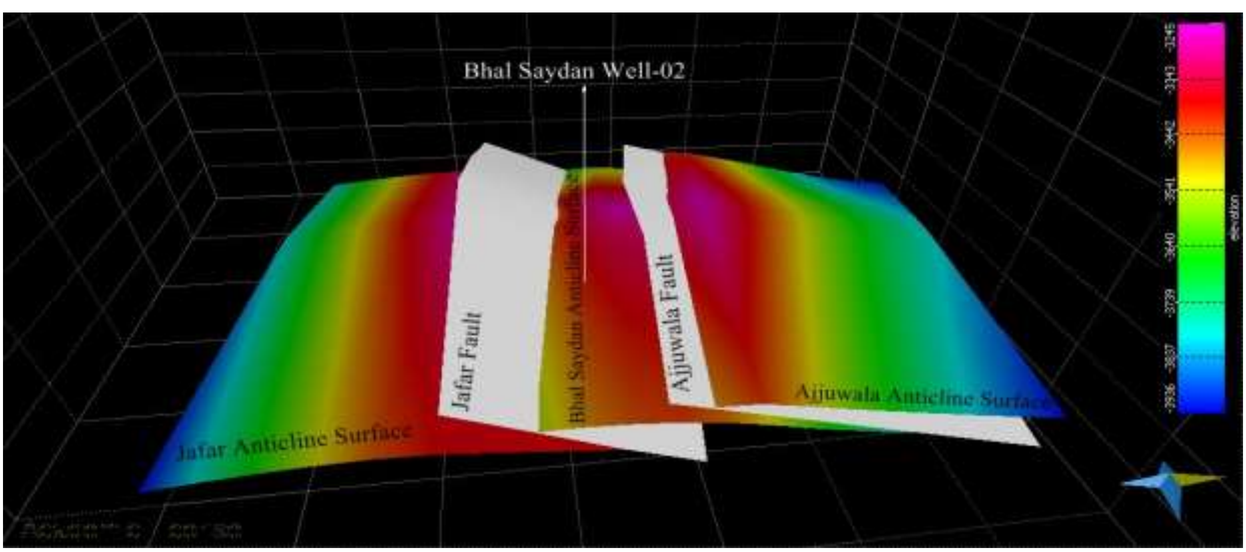

Fig. 5. Showing Bhal Sayedan anticline, Ajjuwala anticline and Jafar anticline surfaces which are fault propagation folds. The Bhal Sayedan anticline and Ajjuwala anticline surfaces are associated with the Jafar and Ajjuwala faults respectively, while the Jafar anticline surface is making an anticline below the Jafar fault.

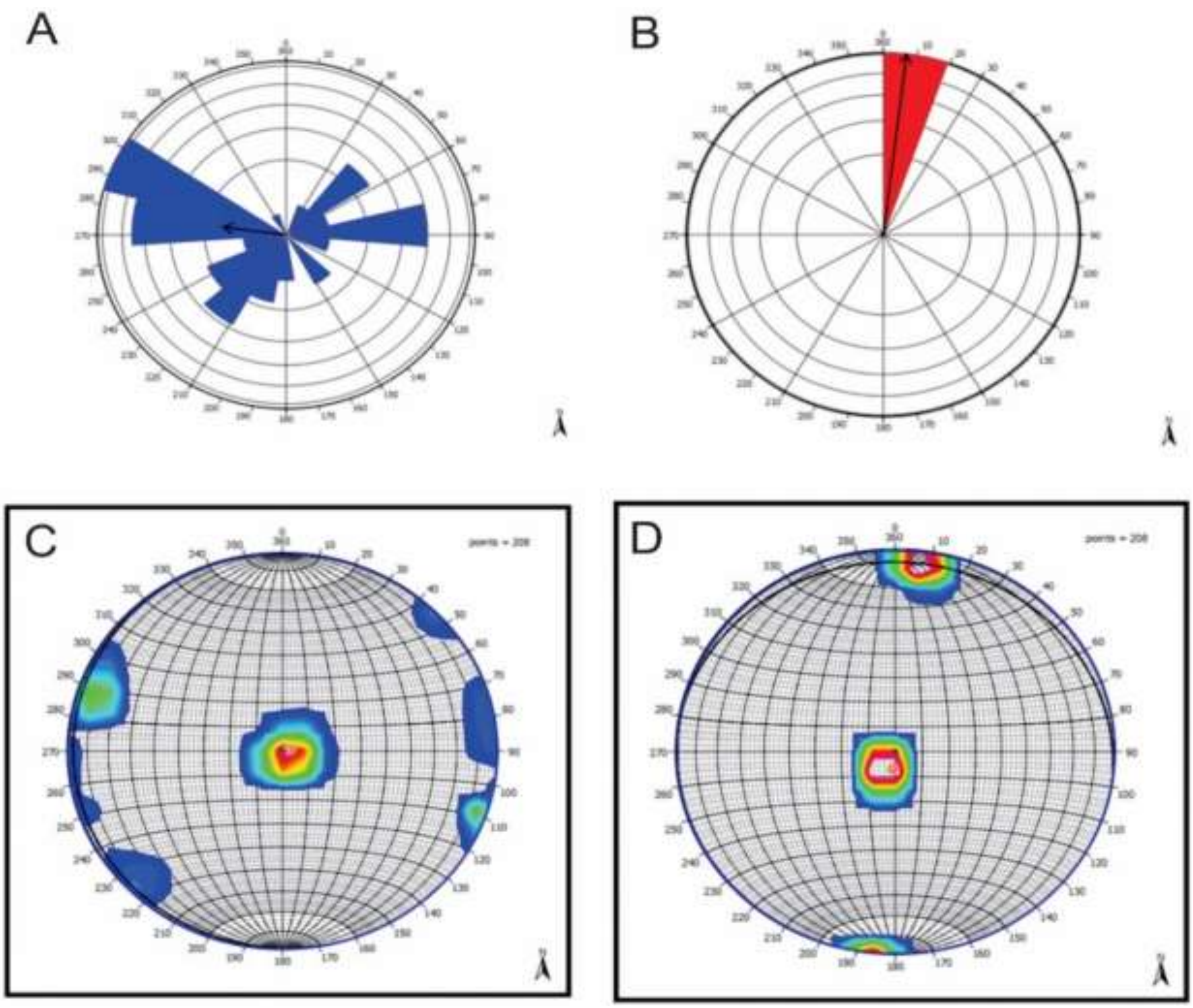

Fig. 6. **A**. Rose plot showing the strike of Bhal Sayedan anticline surface. The average strike is 277° and it is trending N 83° W, S 83° E, **B**. Rose plot showing the dip of the Bhal Sayedan anticline surface which is 7° on average, **C**. Stereo plot showing the mean resultant strike of Bhal Sayedan anticline surface which is trending WNW-ESE, **D**. Stereo plot showing the mean resultant dip of Bhal Sayedan anticline surface. The dip is towards north between 0-20°.

4. Conclusions

The subsurface 3D model constructed through the help of seismic sections and well data indicates;

- The main target horizon for the hydrocarbons exploration is the Bhal Sayedan anticline which is the fault propagation fold that lies between the two thrust faults named as Ajjuwala and Jafar faults.
- The Ajjuwala and Jafar thrust faults are south verging thrust faults with repeated Eocene strata and they are characterized by hanging wall anticlines at the level of Kohat Formation of Early Eocene.
- The reservoir rock is the Kohat Formation which is present at a depth of -3411m interpreted from seismic data.
- The Bhal Sayedan anticline has a four way closure. The back limbs of the

hanging wall anticlines are gently dipping while the fore limbs are short and propagated along the fault planes, hence providing the four way closure.

- A well was drilled over Bhal Sayedan anticline by "X" Oil Company Pakistan in 1990, which is now abandoned. That well was deviated from the top closure of the Bhal Sayedan anticline by 2155m NE so it is suggested that Bhal Sayedan anticline should be drilled for further recovery of oil from Eocene reservoir as the Sadkal oil field just five kilometers east of this location is a good producer of both oil and gas.
- The south verging thrust system, which is formed due to the impact of Main Boundary Thrust (MBT) and has caused the crustal shortening of ~3900m, calculated from the displacement along the two main thrust faults within the research area.

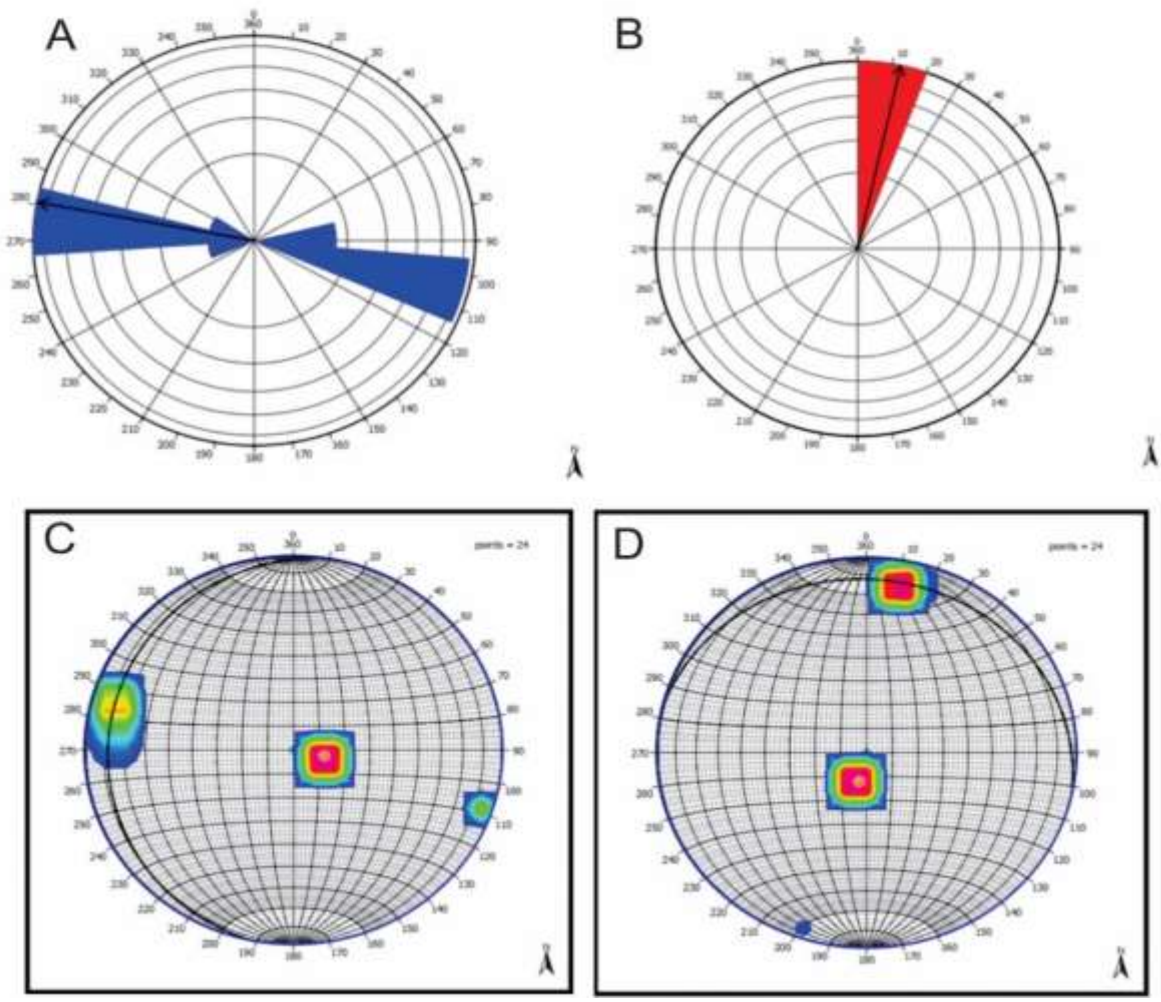

Fig. 7. A. Rose plot showing the strike of the Ajjuwala fault. The average strike is 281° and its trend is N 79° W, B. Rose plot showing the dip of the Ajjuwala fault ranging from 0-20°. The average dip observed is 13°, C. Stereo plot showing mean resultant strike of the Ajjuwala fault trending N 79° W, D. Stereo plot showing the mean resultant dip of Ajjuwala fault which is 0-20° towards north.

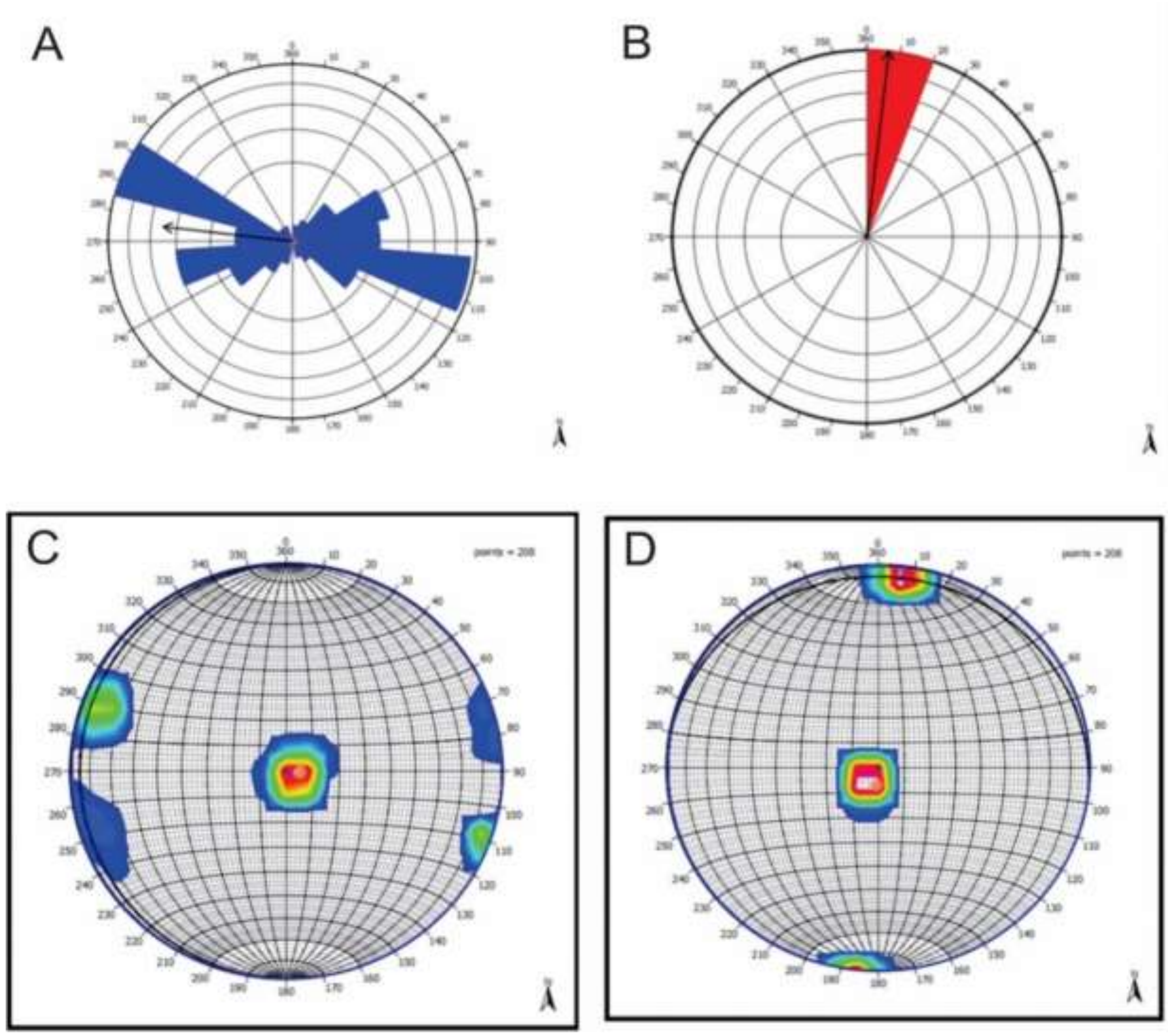

Fig. 8. **A**. Rose plot clearly showing strike of Ajjuwala anticline surface. The average strike is 276° and it is oriented N 80° W, S 80° E, **B**. Rose plot showing dip of Ajjuwala anticline surface, ranging from 0-20°. It is north dipping gentle anticline with an average dip of 7°, **C**. Stereo plot showing the mean resultant strike and mean resultant pole of the strike of Ajjuwala anticline surface. The trend of the strike in general is E-W but actually it is NW-SE, **D**. Stereo plot showing the mean resultant dip of Ajjuwala anticline surface. It is dipping towards the north between 0-10° with an average of 7°.

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Authors' contribution

Salman Ahmed Khattak did overall drafting of the manuscript, interpretation and worked on Move Software. Gohar Rehman provided guidance regarding "Move *software" usage and reviewed the manuscript. Sajjad Ahmad did interpretation of the main structures in the area and linking them with regional tectonics. Muhammad Faisal Jan helped in coral draw software usage. Salman Khurshid did literature review (stratigraphy and Tectonics). Ahmad Ghani worked on Move software.*

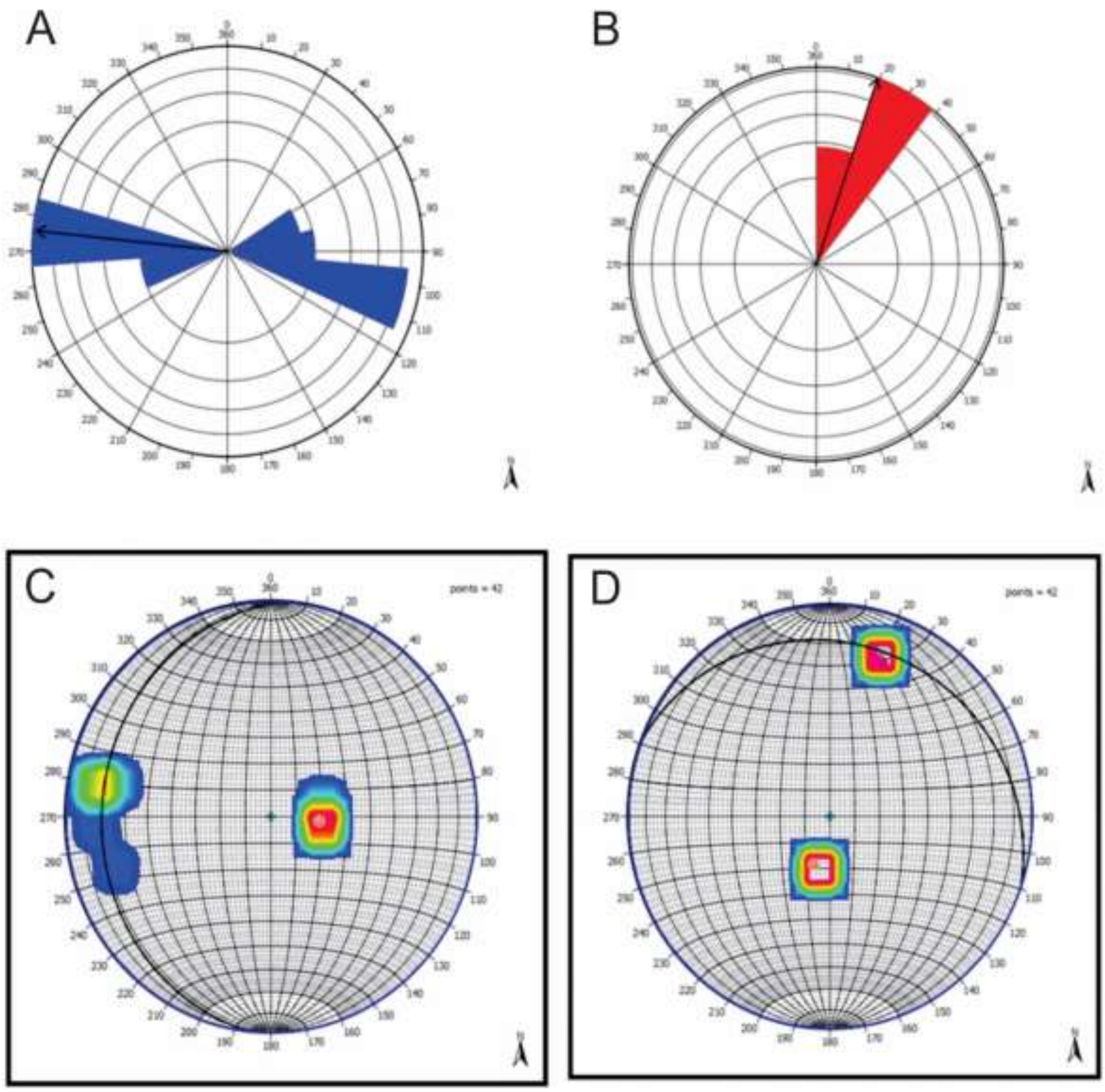

Fig. 9. A. Rose plot showing the strike of the Jafar fault with an average strike of 277°, B. Rose plot showing the dip of the Jafar fault. The average dip observed from the Rose plot is 20°, C. Stereo plot showing the strike of the Jafar fault trending N 83° W. The average strike is 277°, D. Stereo plot showing the dip of the Jafar fault. The average dip is 20°.

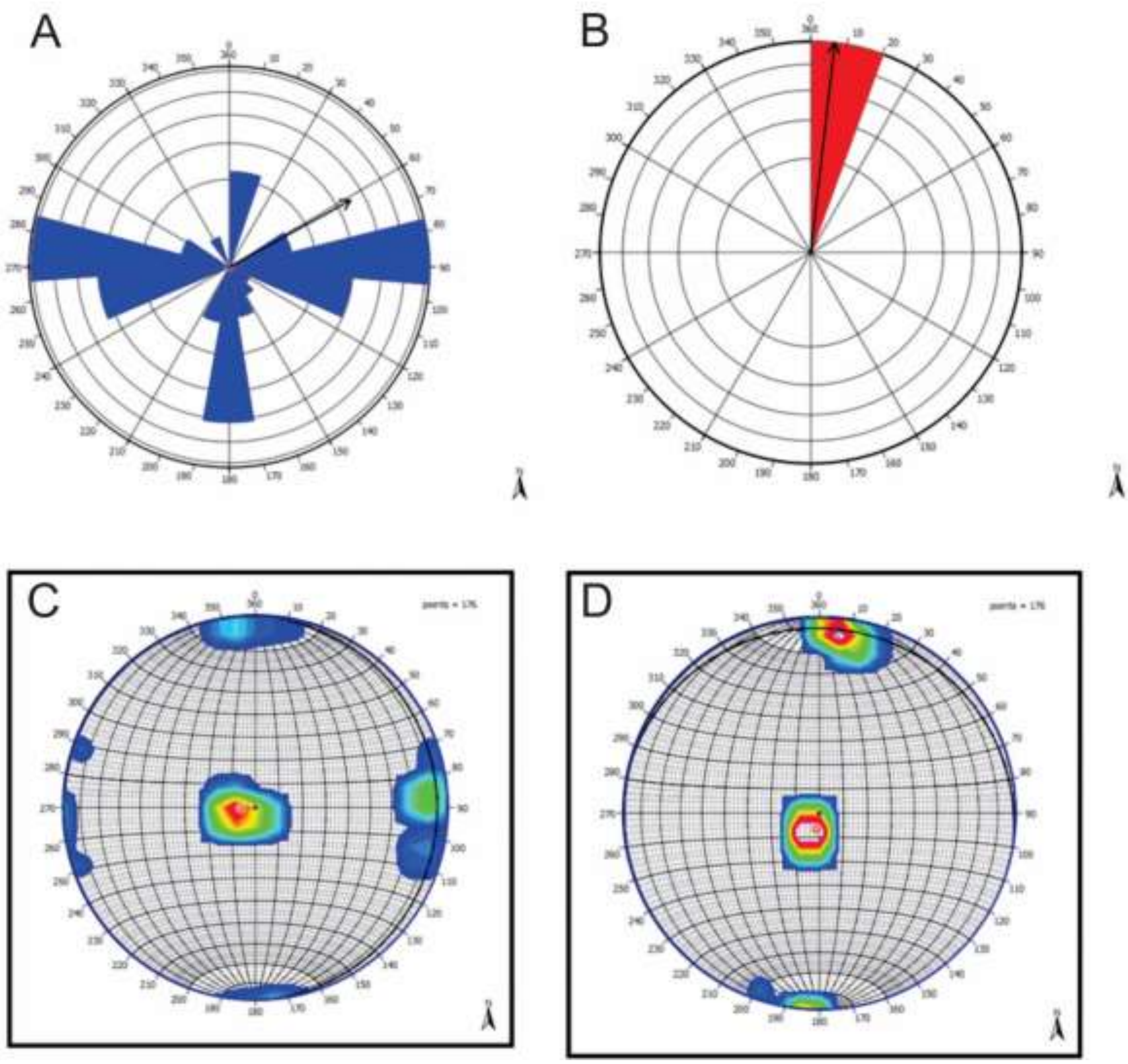

Fig. 10. A. Rose plot showing the strike of the Jafar anticline surface with an average strike of 61°, B. Rose plot showing the dip of Jafar anticline surface ranging from 0-20°. The average dip is 7°, C. Stereo plot showing the mean resultant strike of Jafar anticline surface which is E-W trending, D. Stereo plot showing the mean resultant dip of Jafar anticline surface. The dip of the Jafar anticline surface is towards north between 0-20°.

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